TA5 Project 3:

Time-Dependent Reliability/Durability Methodologies for Acquisition, Maintenance, and Operation of Vehicle Systems

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Report Documentation Page

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Army Needs in Reliability, Maintenance and Logistics

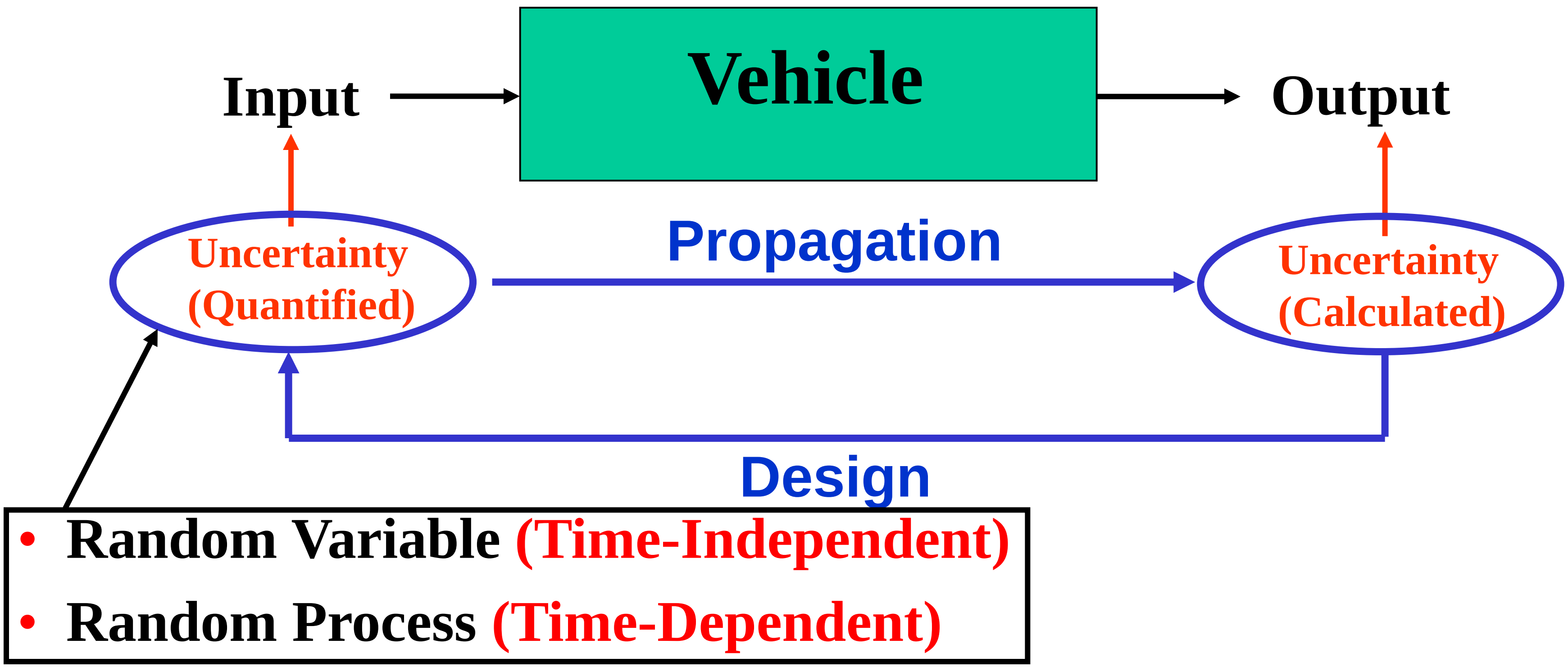
- **Reduce operations and maintenance costs**
- **Increase effectiveness of fleet logistics**
- **Control lifecycle cost and also use it in design and procurement**
- **Improve availability; schedule maintenance**

Excerpts from Memorandum dated 27 Mar 2004

. …..Published studies and audits have documented that reliability has a significant impact on **mission effectiveness, logistics effectiveness, and life-cycle costs**….”

General, United States Army
Vice Chief of Staff

Background



Challenges:

- **Quantification of a Random Process**
- **Estimation of time-dependent reliability**

Research Statement

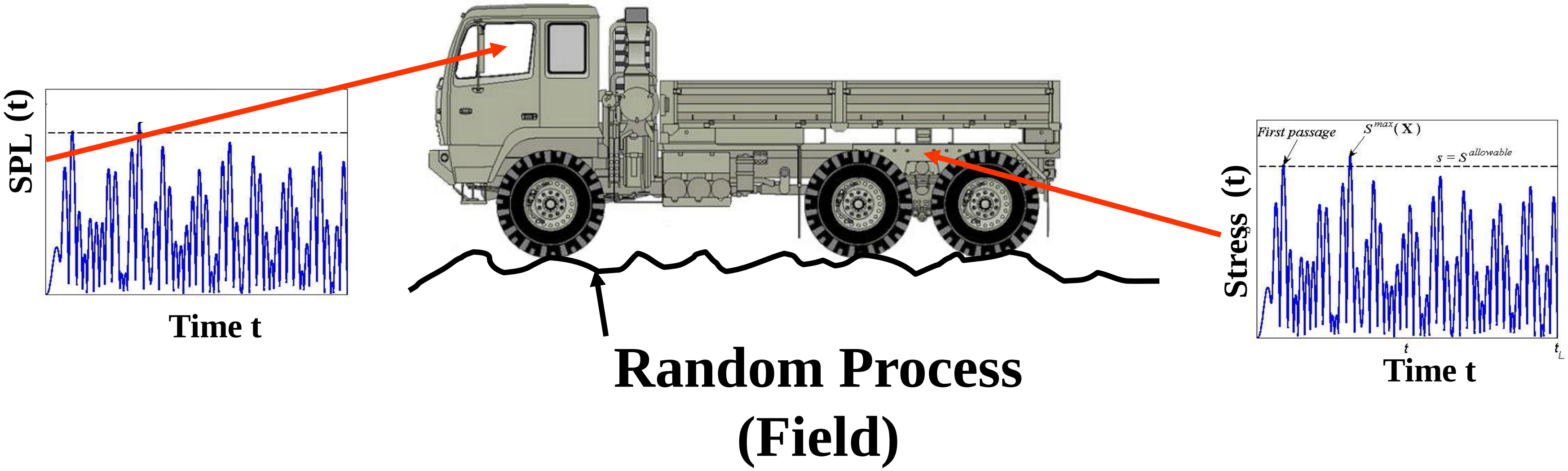
- Develop methodologies to assess and improve the reliability / durability of vehicle systems using
  - Experimental (field) data
  - “Expert” opinion
  - Predictive tools (physics-of-failure data)

Previously and currently at TARDEC

Current research

- Use methodologies in design for lifecycle cost and preventive maintenance

Background



Input
Random Process → **Vehicle** → **Output**
Random Process

Random Process leads to Time-Dependent Reliability

What is Reliability?
Cumulative Probability of Failure

Reliability at time t is the probability that the system has not failed before time t.

$$F_T^c(t_L) = P\left(\exists t \in [0, t_L], \; such \quad that \quad g(\mathbf{X}(t), t) \le 0\right)$$

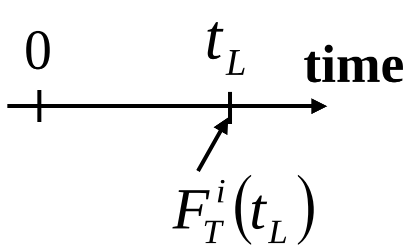
Cumulative Prob. of Failure

$$F_T^i(t_L) = P\left(g(\mathbf{X}(t_L), t_L) \le 0\right)$$

Instantaneous Prob. of Failure

Time-Invariant Reliability

Time-Variant Reliability



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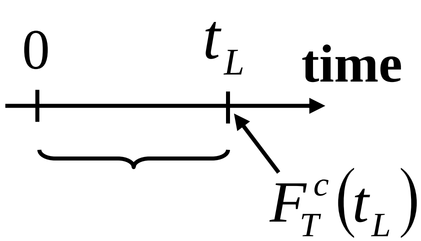
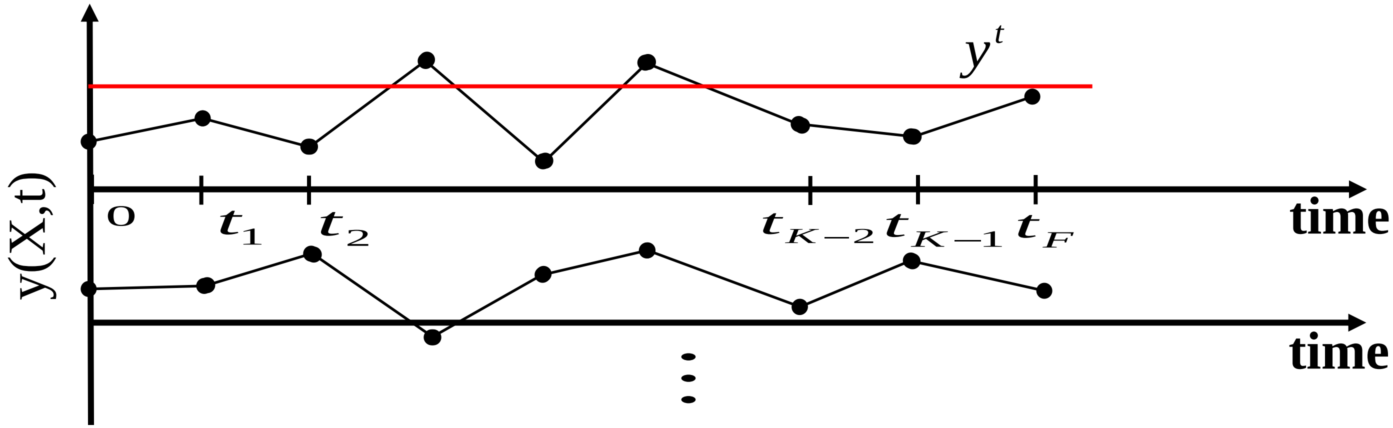


Calculation of Cumulative Probability of Failure

Maximum Response Approach



$$y^{\max}(\mathbf{X}) = \max_{t_{\min} \le t \le t_{\max}} y(\mathbf{X}, t)$$

$$\boxed{F_T^c(t_F) = P(y^{\max}(\mathrm{X}) \ge y^t) = P(y^t - y^{\max}(\mathrm{X}) \le 0)}$$

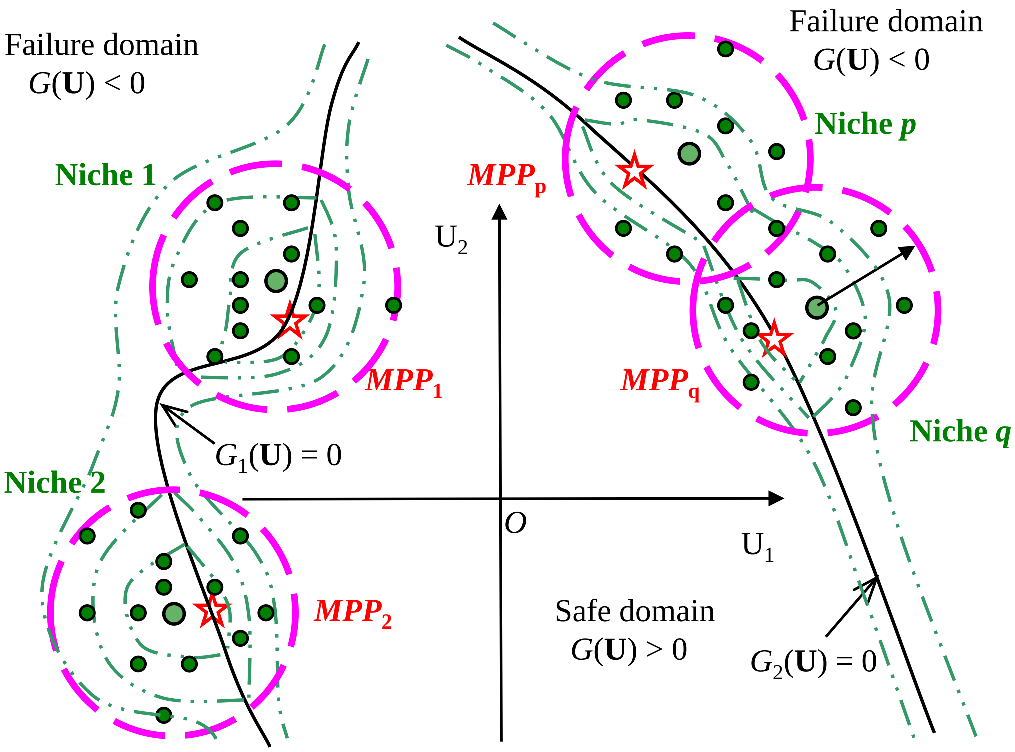
Time-independent composite limit state is defined as:

$$g(\mathbf{X}) = y^t - y^{\max} \le 0$$

Calculation of Cumulative Probability of Failure

Niching GA & Lazy Learning Local Metamodeling

- **Observations:**
  - ✓ Niche center is an approximate MPP
  - ✓ Niching GA finds ALL approximate MPPs



- **Local metamodels are driven by Niching GA exploration for multiple MPPs**
  - Error control using cross-validation

Definition of Lifecycle Cost

Lifecycle Cost = Production Cost

+ Inspection Cost

+ Expected Variable Cost

Quality

Time-Dependent System Reliability

Definition of Lifecycle Cost

$$C_L(\mathbf{d},\mathbf{X},t_f,r) = C_P(\mathbf{d},\mathbf{X}) + C_I(\mathbf{d},\mathbf{X},t_0) + C_V^E(\mathbf{d},\mathbf{X},t_f,r)$$

Lifecycle Cost

Production Cost

Inspection Cost

Expected Variable Cost

Final time

Interest rate

$$C_V^E(\mathbf{d},\mathbf{X},t_f,r) = \int_0^{t_f} c_F(t)\, e^{-rt} f_T^c(t)\, dt$$

Cost of failure at time t

PDF of time to failure time

$$F_T^c(t_L) = P\left(\exists t \in [0,t_L],\ such \quad that \quad g(\mathbf{X}(t),t) \le 0\right)$$

Using a Target System Reliability in Time

$$\min_{\mathbf{d},\boldsymbol{\mu}_\mathbf{X},\boldsymbol{\sigma}_\mathbf{X}} C_L\left(\mathbf{d},\boldsymbol{\mu}_\mathbf{X},\boldsymbol{\sigma}_\mathbf{X},t_f,r\right)$$

$$\text{s. t. } F_T^{i}\left(\mathbf{d},\mathbf{X},t_0\right)\le p_f^t\left(t_0\right)$$

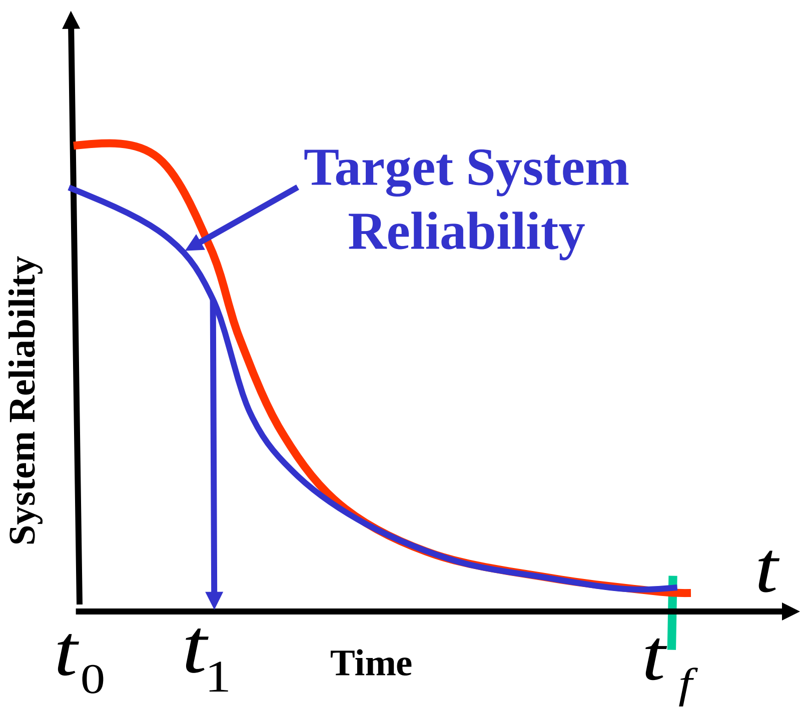
$$F_T^{c}\left(\mathbf{d},\mathbf{X},t_1\right)\le p_f^t\left(t_1\right)$$

$$F_T^{c}\left(\mathbf{d},\mathbf{X},t_f\right)\le p_f^t\left(t_f\right)$$

$$\mathbf{d}_L\le\mathbf{d}\le\mathbf{d}_U$$

$$\boldsymbol{\mu}_{\mathbf{X}_L}\le\boldsymbol{\mu}_\mathbf{X}\le\boldsymbol{\mu}_{\mathbf{X}_U}$$

$$\boldsymbol{\sigma}_{\mathbf{X}_L}\le\boldsymbol{\sigma}_\mathbf{X}\le\boldsymbol{\sigma}_{\mathbf{X}_U}$$



Estimation of Time for Preventive Maintenance

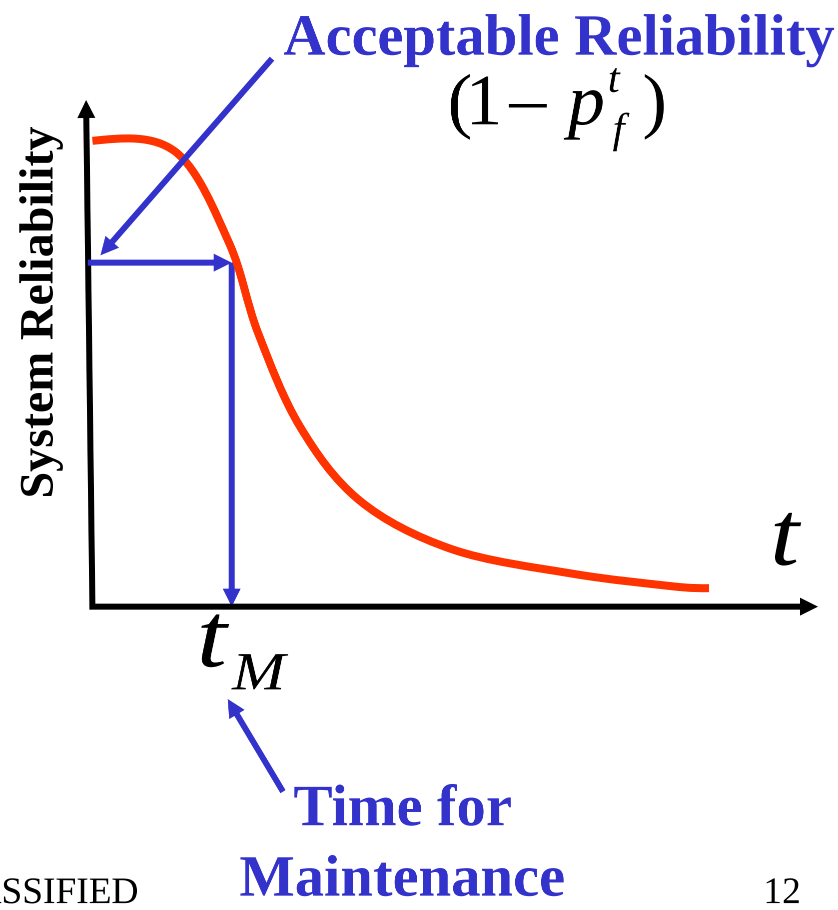
$$\min_{\mathbf{d},\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}}} C_P\left(\mathbf{d},\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}}\right)+C_I\left(\mathbf{d},\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t_0\right)$$

s. t. $F_T^c\left(\mathbf{d},\mathbf{X},t_M\right)\le p_f^t$

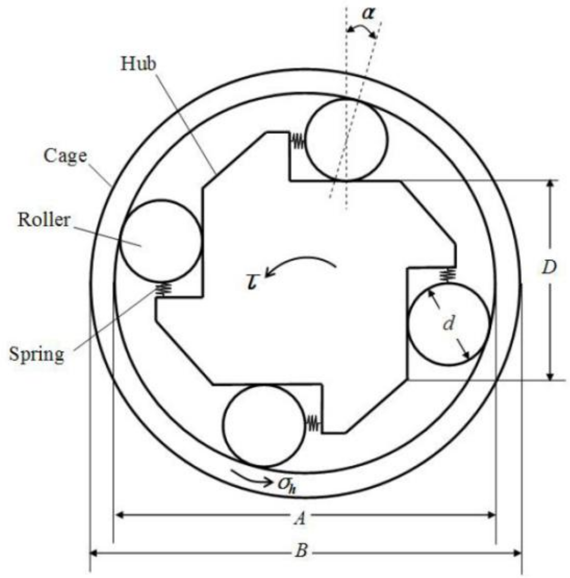
$$\mathbf{d}_L \le \mathbf{d} \le \mathbf{d}_U$$

$$\boldsymbol{\mu}_{\mathbf{X}_L} \le \boldsymbol{\mu}_{\mathbf{X}} \le \boldsymbol{\mu}_{\mathbf{X}_U}$$

$$\boldsymbol{\sigma}_{\mathbf{X}_L} \le \boldsymbol{\sigma}_{\mathbf{X}} \le \boldsymbol{\sigma}_{\mathbf{X}_U}$$



Design of a Roller Clutch



Random Variables: D, d, A

Due to degradation:

$$\mathbf{D} \rightarrow \mathbf{D}(1-kt)$$

$$\mathbf{d} \rightarrow \mathbf{d}(1-kt)$$

$$\mathbf{A} \rightarrow \mathbf{A}(1+kt)$$

with: $k = 2.5E-04 \quad mm/year$

Constraints:

- **Contact angle** $\alpha = 0.11 \pm 0.06$ rad
- **Torque** $\tau >= 3000$ Nm
- **Hoop stress** $\sigma_h \leq 400 \quad MPa$

$$g_1(D,d,A) = 0.05 - \cos^{-1}\left(\frac{D-d}{A-d}\right) \leq 0$$

$$g_2(D,d,A) = \cos^{-1}\left(\frac{D-d}{A-d}\right) - 0.17 \leq 0$$

$$g_3(D,d,A) = 3000 - NL\left(\frac{\sigma_c}{c_1}\right)^2 \frac{D^2 d}{4(D+d)}\sqrt{1-S^2} \leq 0$$

$$g_4(D,d,A) = \frac{N}{2\pi}\left(\frac{\sigma_c}{c_1}\right)^2\left(\frac{Dd}{(D+d)}\right)\frac{S}{A}\left(\frac{B^2+A^2}{B^2-A^2}\right) - 400E06 \leq 0$$

Roller Clutch: Problem Statement

Minimize
Lifecycle Cost

$$\min_{\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}}} C_L\left(\boldsymbol{\mu}_{\mathbf{x}},\boldsymbol{\sigma}_{\mathbf{X}},t_f,r\right)$$

$$\boldsymbol{\sigma}_{\mathbf{X}_L} \le \boldsymbol{\sigma}_{\mathbf{X}} \le \boldsymbol{\sigma}_{\mathbf{X}_U}$$

$$\boldsymbol{\mu}_{\mathbf{X}_L} \le \boldsymbol{\mu}_{\mathbf{X}} \le \boldsymbol{\mu}_{\mathbf{X}_U}$$

s. t.

Case 1

$$F_T^i\left(\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t_0=0\right)= P\left(\bigcup_i^4 \left(g_i(D,d,A,t_0)<0\right)\right)\le p_f\left(t_0=0\right)=0.0013$$

Case 2

$$F_T^i\left(\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t_0=0\right)= P\left(\bigcup_i^4 \left(g_i(D,d,A,t_0)<0\right)\right)\le p_f\left(t_0=0\right)=0.0013$$

$$F_T^c\left(\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t=7.5\right)= P\left(\bigcup_i^4 \left(g_i(D,d,A,t)<0\right)\right)\le p_f\left(t=7.5\right)=0.005$$

Case 3

$$F_T^c\left(\boldsymbol{\mu}_{\mathbf{X}},\boldsymbol{\sigma}_{\mathbf{X}},t=10\right)= P\left(\bigcup_i^4 \left(g_i(D,d,A,t)<0\right)\right)\le p_f\left(t=10\right)=0.0716$$

Roller Clutch: Problem Statement

where:

Total Cost, $C_L = C_P + C_I + C_V^E$

$$C_P = \left(3.5 + \frac{0.75}{3\sigma_D}\right) + \left(3.0 + \frac{0.65}{3\sigma_d}\right) + \left(0.5 + \frac{0.88}{3\sigma_A}\right)$$

$$C_I = 20 F_T^i(\mathbf{X}, t_0)$$

Scrap cost/unit

$$C_V^E = \int_0^{t_f} 20 e^{-rt} f_T^c(t)\,dt$$

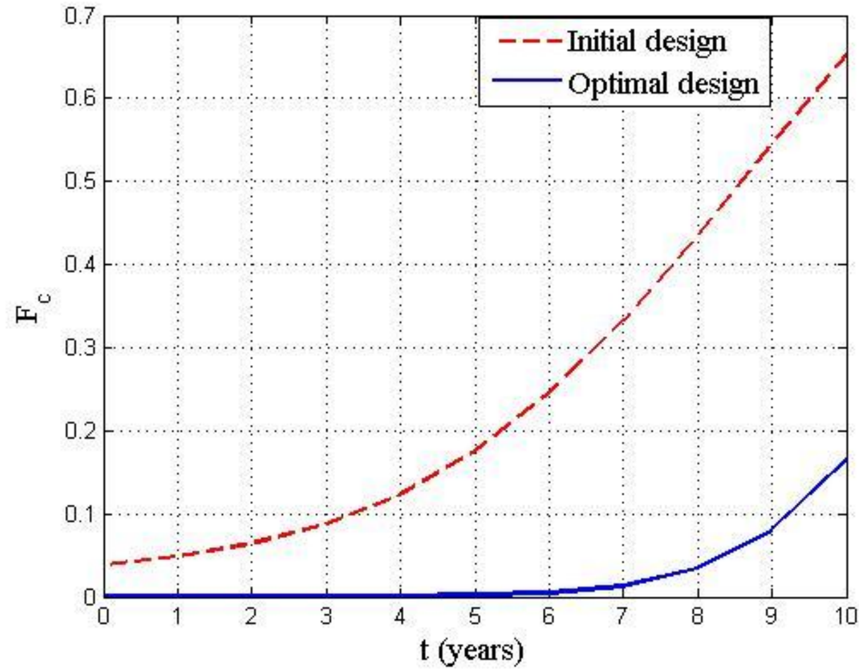
Failure cost/unit (warranty cost)

$t_f = 10 \quad years$

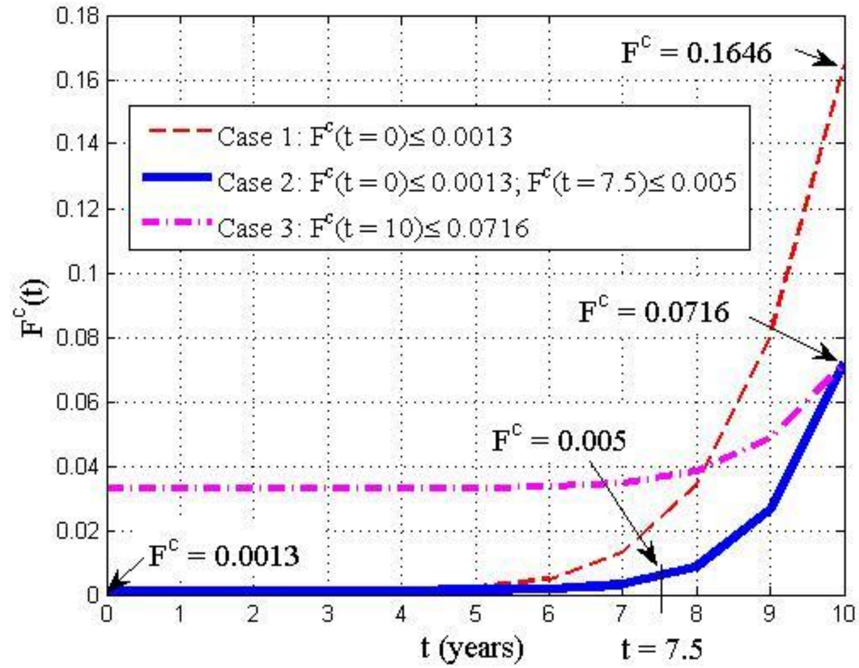
$r = 3\%$

Roller Clutch: Results

Initial Design vs. Case 1



Case 1 vs. Case 2 and Case 3

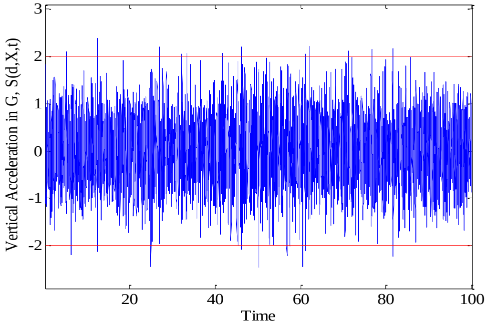


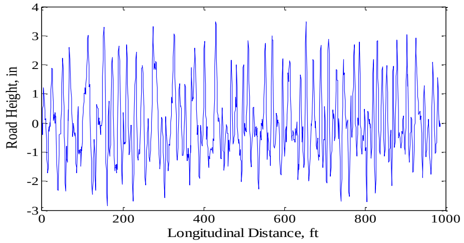
		Initial Design	Optimal Design		
			Case 1	Case 2	Case 3
Objective	Total Cost	28.2275	23.876	24.5440	21.1896
	Production Cost	17.3900	21.3340	23.4446	19.9383
	Inspection Cost	0.7677	0.0260	0.0260	0.6596
	Expected Variable Cost	10.0697	2.5161	1.07340	0.5918

A Practical Issue

Random Variables

Vertical Accel. (G)





Terrain

Vehicle speed : 20 mph; Mission distance : 100 miles

Simulation can be practically performed for a short-duration time

Solution to Practical Issue

A novel MC-based method has been developed to calculate the time-dependent reliability (cumulative probability of failure) using short-duration data based on:

- **Exponential extrapolation**
- **Poisson's distribution**

Time-Series Modeling

Can characterize a stationary or non-stationary input Random Process

AR, ARIMA, GARCH, ….

$$u_i - \bar{u} = \phi_1(u_{i-1} - \bar{u}) + \phi_2(u_{i-2} - \bar{u}) + \ldots \phi_p(u_{i-p} - \bar{u}) + \varepsilon_i$$

Must estimate $\phi_p, \quad \sigma_e^2$

Cumulative Probability of Failure

$$R(t) = 1 - F_T^c(t) \qquad \textbf{(1)}$$

Failure Rate

$$\lambda(t) = \frac{P(t < T \le t + dt / T > t)}{dt} = \frac{P(t < T \le t + dt)}{dt * P(T > t)} =$$

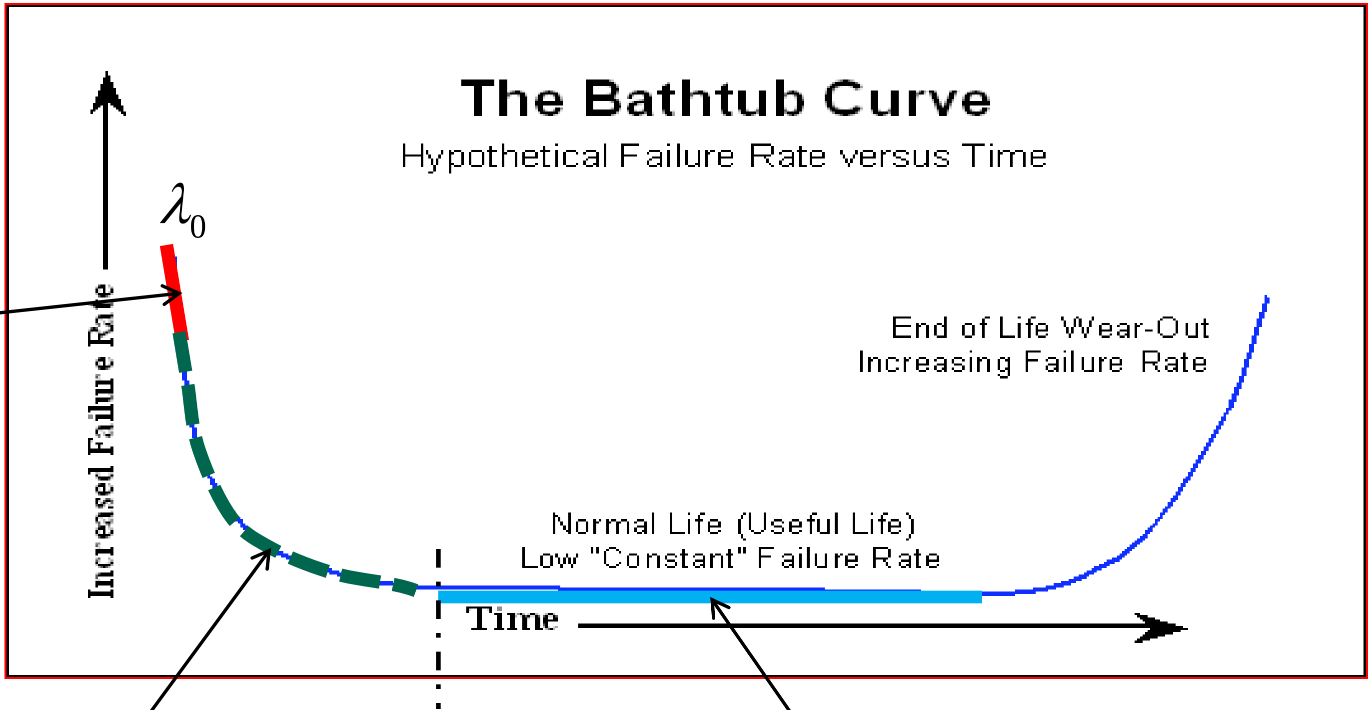
$$= \frac{F(t+dt) - F(t)}{dt * R(t)} \Rightarrow \boxed{\lambda(t) = \frac{f(t)}{1 - F_T^c(t)}} \qquad \textbf{(2)}$$

From (1) and (2):

$$\boxed{F_T^c(t) = 1 - \exp[-\int_0^t \lambda(t) dt]}$$

All we need is the failure rate

Efficient MCS-based Approach



t_{int}

MCS

$$b = -\frac{1}{\lambda_0}\left(\frac{d\hat{\lambda}}{dt}\right)_{t=0}$$

Exponential Extrapolation

$$\boxed{\hat{\lambda}(t) \approx \lambda_0 e^{-bt}}$$

Poisson's Formula

$$F_T^c(t) = \begin{cases} 1 - e^{-\int_0^t \hat{\lambda}(t)dt} & , t \in [0, t_{\text{int}}] \\ 1 - (1 - F_T^c(t_{\text{int}}))e^{-\lambda_m (t - t_{\text{int}})} & , t \in [t_{\text{int}}, t_f] \end{cases}$$

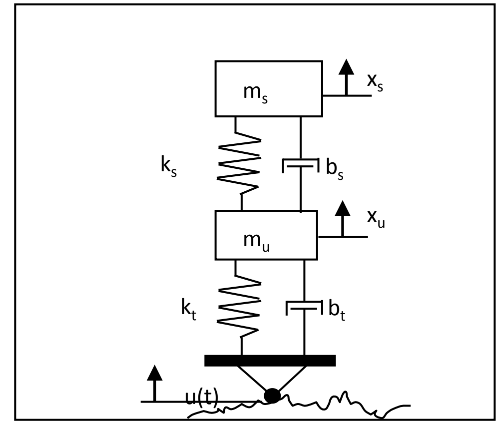
Quarter-Car Model on Stochastic Terrain

Constant design parameters:

m_s =1000 kg

m_u =100 kg

Vehicle speed = 20 mph



Random Input variables

Damping, $b_s \sim N(7000, 1400^2)$

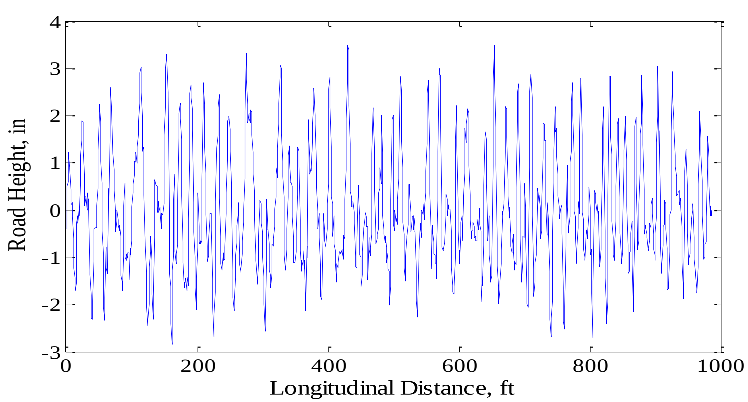
Stiffness, $k_s \sim N(40\times10^3, (4\times10^3)^2)$

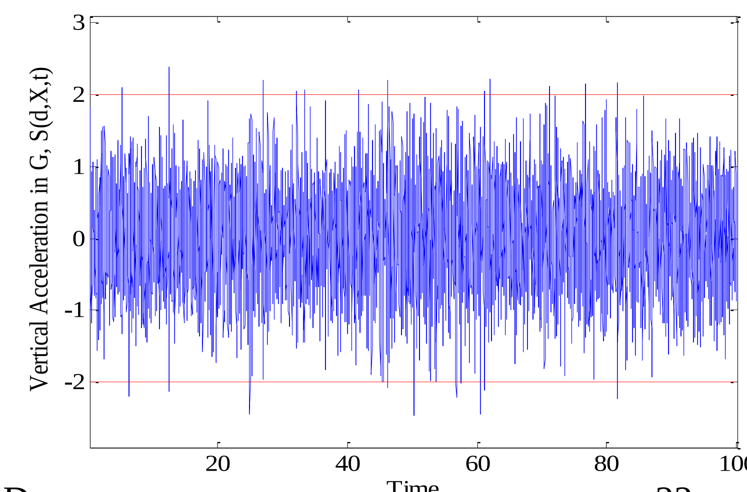
Random Output Process

(Vertical Acceleration, G')

Random Input Process: Experimental Stochastic Terrain from Yuma Proving Grounds.

Threshold = 2G

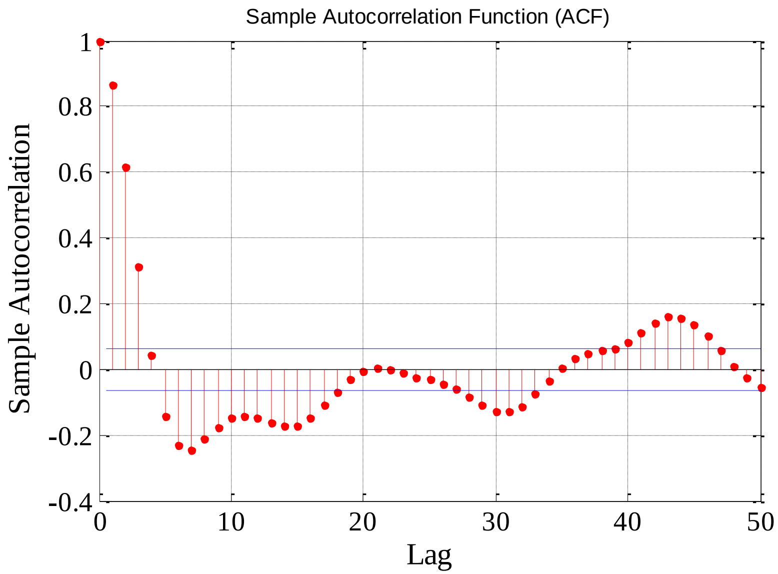




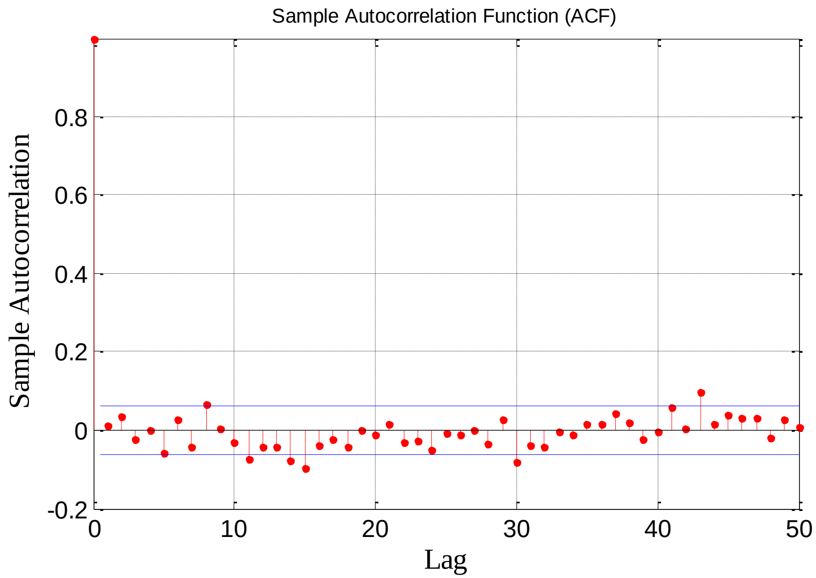
Quarter-Car Model: Road Input Random Process Characterization

AR(3) model was identified based on:

Autocorrelation Function



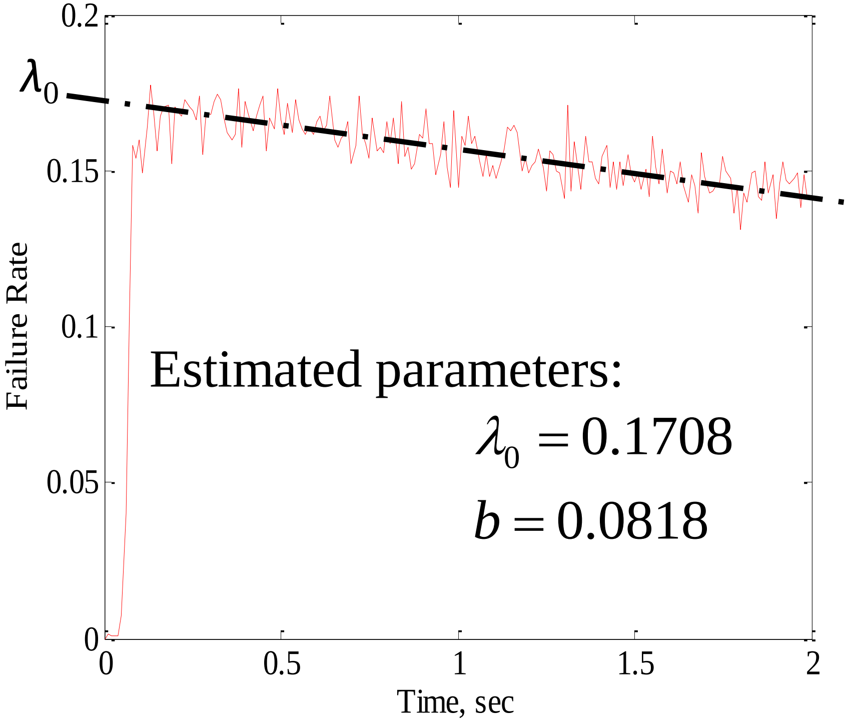
Autocorrelation of Residual process

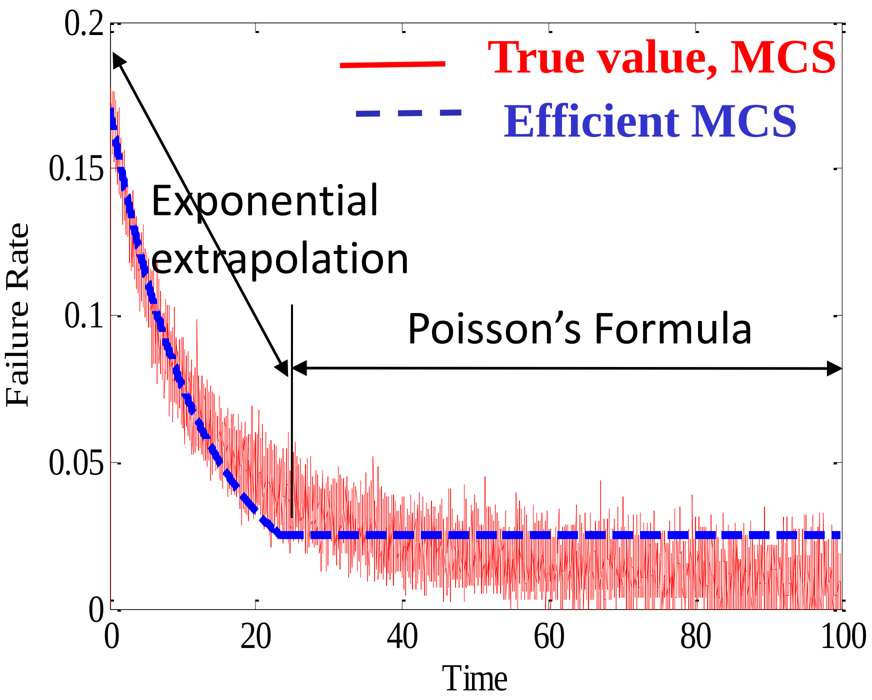


$$u_i = 1.2456 \quad u_{i-1} - 0.2976 \quad u_{i-2} - 0.1954 \quad u_{i-3} + \varepsilon_i(0, \quad 0.5132^2)$$

Statistical tests were performed to verify the model

Quarter-Car Model: Results
(Failure Rate Estimation for Threshold = 2G)





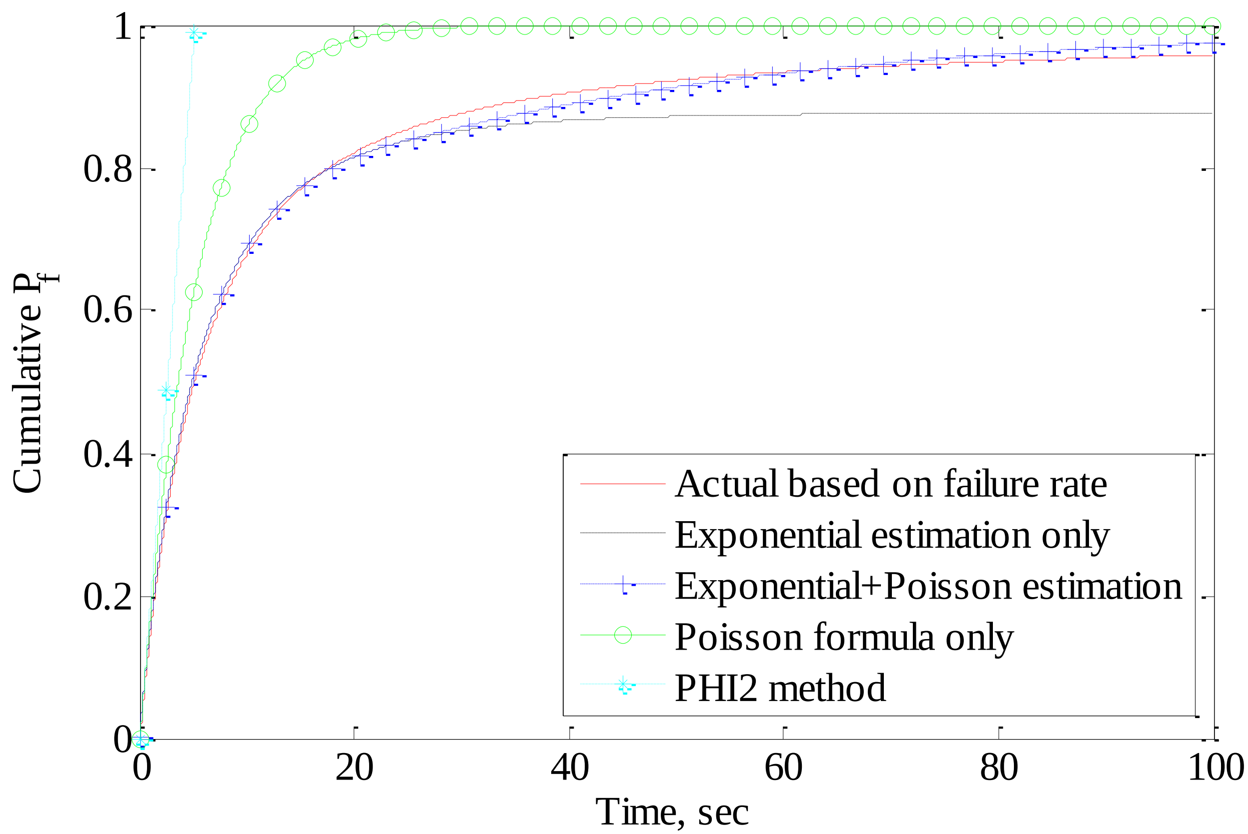
Estimation requires short duration MCS

Exponential extrapolation

$$\hat{\lambda}(t) \approx \lambda_0 e^{-bt}$$

Quarter-Car Model: Results

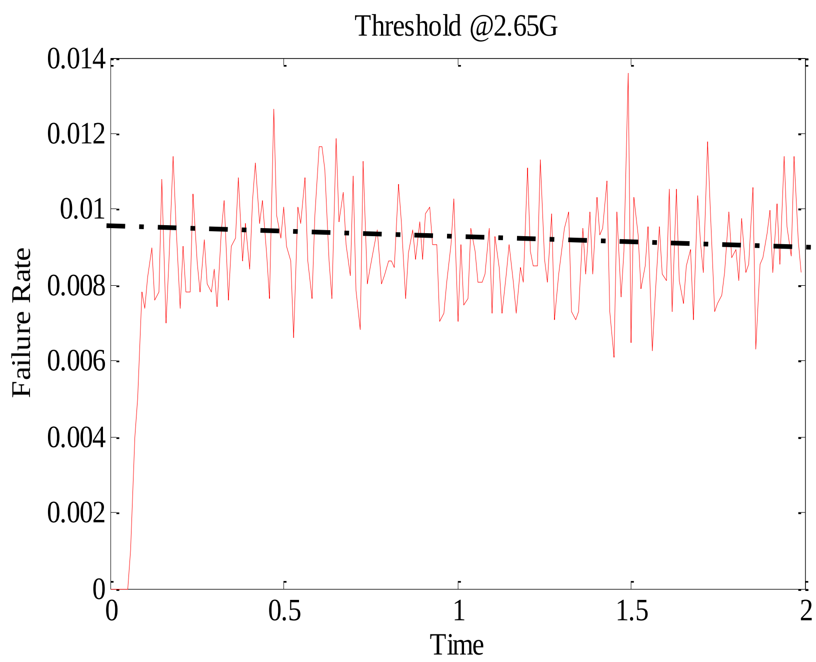
Cumulative Probability of Failure for Threshold = 2G



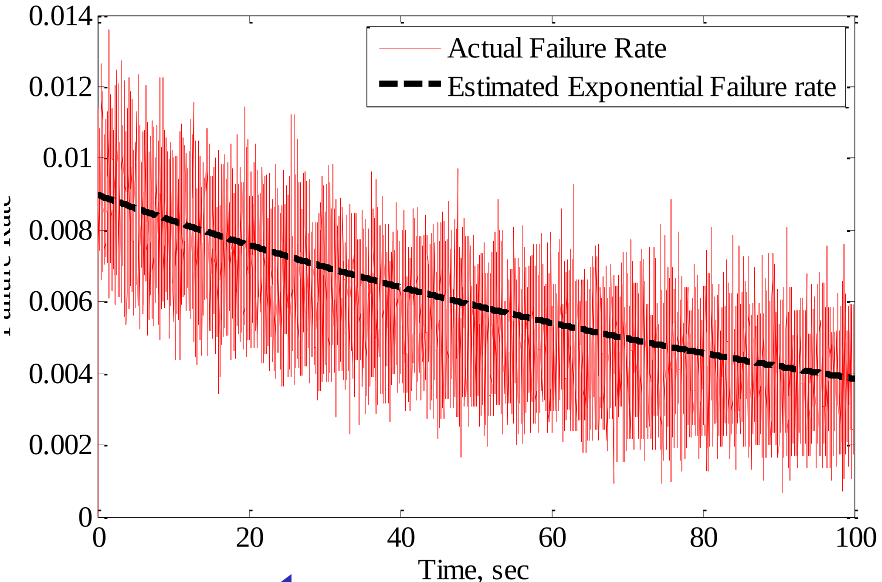
Efficient MCS (blue) approach is close to true MCS results (red)

Quarter-Car Model: Results
(Failure Rate Estimation for Threshold = 2.65 G)

Estimation Using Short Time



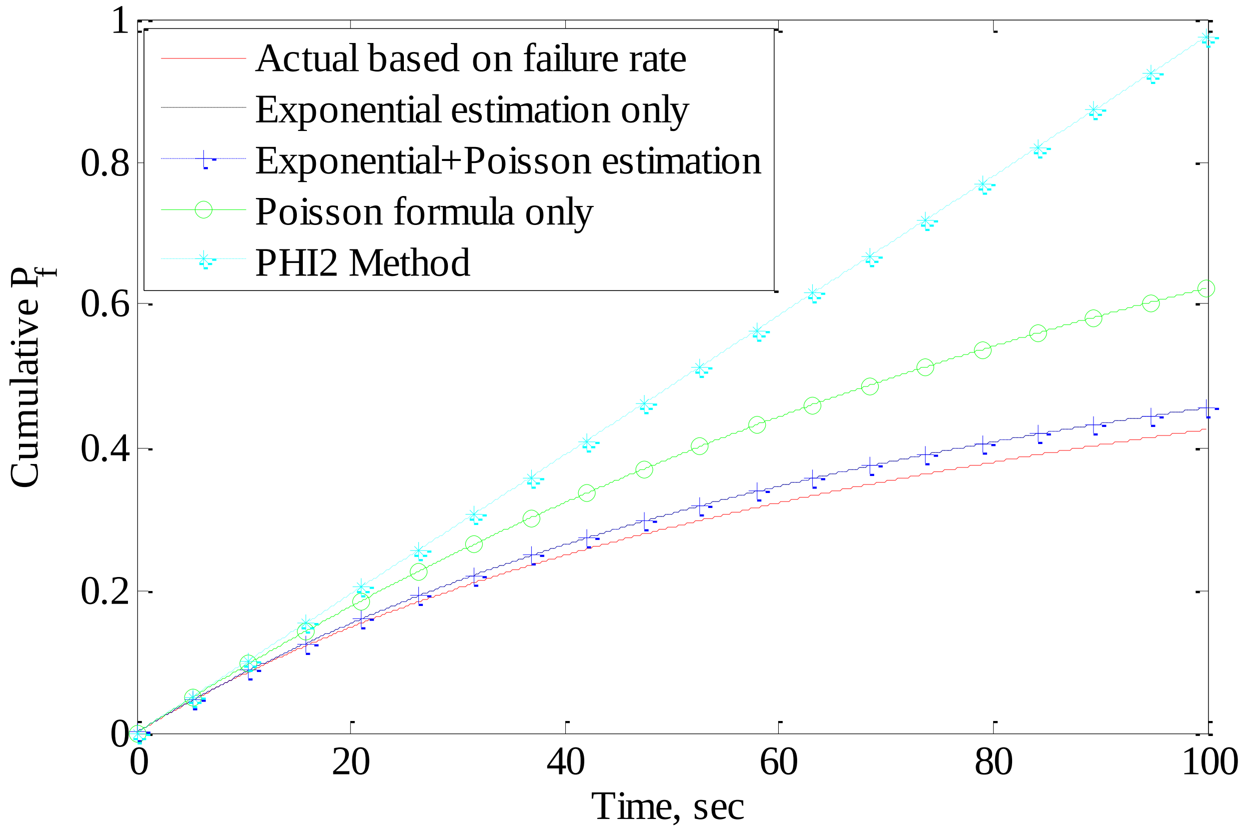
Extrapolation Over Remaining Time



Estimated failure rate (black) is close to true failure rate (red)

Quarter-Car Model: Results

Cumulative Probability of Failure for Threshold = 2.65 G



Efficient MCS (blue) approach is close to true MCS results (red)

Summary

- Time-dependent reliability methodologies have been developed using math-based models.
- An approach to design for lifecycle cost and preventive maintenance has been developed.
- A novel MC-based approach was developed, using short-duration data, to compute time-dependent reliability in the presence of an input random process.
- Examples demonstrated the developed methods.

Future Work

- Develop an importance sampling method to improve the computational effort in estimating the time-dependent reliability of systems with a stationary and non-stationary input random process (June 2010).
- Demonstrate potential of developed methods in preventive maintenance (August 2010).
- Combine current research developments with existing or under development efforts at TARDEC in reliability area (December 2010).

Thanks for your attention !

Q & A

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